Multi –Conjugate Adaptive Optics Test-bed for horizontal propagation

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ABSTRACT

Our program for the upgrade of the Naval Prototype Optical Interferometer with large telescopes and adaptive optics has produced a test-bed for the in system evaluation and testing of our MEMs adaptive optics components and system performances. We have already reported in recent publications the basic characteristics of the test-bed. In order to improve the capabilities of such laboratory set-up we have started an upgrade that aims at developing a Multi Conjugate Adaptive Optics (MCA) test-bed. This test bed is based on the use of multiple Liquid Crystal Spatial Light Modulators (LCSLMs) for producing different phase screens at different spatial locations within the set-up. Details of this new set-up are presented in another paper in these proceedings. This paper specifically deals with the analytic portion of the MCAO test-bed.

INTRODUCTION

Our program has been focused on the development of light weight and low cost adaptive optics. For the past several years we have been testing devices and systems based on two main technologies, liquid crystals (LC) and MEMS.
Recent advances in manufacturing capabilities have resulted in many new electro optical devices being developed for use in Adaptive Optics (AO) systems. These devices include MEMS [1, 2], liquid crystal devices [3], deformable secondary telescope mirrors [4] and emerging technologies using composite materials [5]. With so many of these systems coming available there is a significant need to be able to consistently evaluate and characterize the performance of these devices.

Traditionally the performance of an atmospheric compensation device is evaluated either as part of a full AO system using astronomical targets or in static, laboratory tests using lasers and fixed aberrations. What is desired is a system that can consistently and repeatably generate a phase screen similar to the atmosphere but under direct user control.

We also want to explore the use of multiple phase screens to simulate the generation of scintillation or alternatively the generation of phase screens that can reproduce the effect on wide Field Of View (FOV) systems.

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One of the most important aspects of these test-bed is the ability of accurately predicting what type of aberrations are generated and then compare with the experimental data in order to determine the characteristics and performances of the AO system.

This paper reports on the analytic tools and performance forecasts developed for the MCA AO.

2. Phase Screen Simulator and Propagator

The geometry of the problem is based on the set-up of the test-bed. We have two LCSLMs that can generate independently a phase screen, these two phase screen are separated by a distance Δz_1. Following these two phase screens there are two Deformable Mirrors (DMs) that can be positioned at a conjugate plane of each of the two LCSLMs or in different planes. This will allow us to study the effect of when a DM is not in the right conjugate plane. We use the Fresnel propagation to evaluate all the pertinent parameters. In specific we will use the Fourier transform approach for the evaluation of the Fresnel propagator.

The field on the plane (x_0,y_0) is related to the field on the initial plane (x_1,y_1), at a distance z, through the Fresnel integral:

$$U(x_0\ ,y_0\ ) = \frac{e^{ikz}}{iyz}\iint_{-\frac{l}{2}}^{\frac{l}{2}} u(x_1\ ,y_1\ )e^{\{ik/2z[(x_1-x_0)^2+(y_1-y_0)^2]\}}dx_1 dy_1 \quad [1]$$

In order to compute the Fresnel integral between multiple planes it is computationally convenient to use the Fourier transform approach. We follow the standard technique illustrated in [6]. If we have n planes each described by a complex transmission function $T_n(x,y)$ the field transmitted through the plane $z=z_n$ is equal to the field incident on that plane times the complex transmission function of that plane. In other words, if $u(x,y)_z$ is the field incident on the first plane z_1, the transmitted field in the region $z_1 \leq z \leq z_2$ is given by

$$u(x,y)_z = \mathcal{F}^{-1}\left\{\tilde{U}\left(f_x,f_y\right)_{z1} exp[2\pi i f_z(z-z_1)]\right\} \qquad [2]$$

Where $\mathcal{F}$ and $\mathcal{F}^{-1}$ represent the direct and inverse Fourier transform, respectively, and

$$\tilde{U}\left(f_x,f_y\right)_{z1} = \mathcal{F}\{u(x,y)_{z1}T_1(x,y)\} \qquad [3]$$

f_z is given by:

$$f_z = \begin{cases} \left(\frac{1}{\lambda^2} - f_t^2\right)^{1/2} & if\ f_t^2 = f_x^2 + f_y^2 \leq 1/\lambda^2 \\ i\left(f_t^2 - \frac{1}{\lambda^2}\right)^{1/2} & if\ f_t^2 = f_x^2 + f_y^2 > 1/\lambda^2 \end{cases} \qquad [4]$$

Where f_x and f_y are the spatial frequencies.

The complex transmission function for the two planes is built using Zernike polynomials according to Noll's description [7]. However, any other description of a phase screen is of course possible. In this paper we restrict ourselves this approach for sake of simplicity. The influence functions for a continuous, thin membrane MEM mirror are given by solving the Poisson equation [8]:

$$\nabla^2 S(x,y) = \frac{P}{T} \qquad [5]$$

Where $S(x,y)$ represents the surface deflection of the membrane, T is tension of the membrane and the electrostatic pressure P is give by

$$P = \frac{\varepsilon\varepsilon_0 V(x,y)^2}{d(x,y)^2} \qquad [6]$$

In eq.(6) V is the applied voltage at the point (x,y) and $d(x,y)$ is the distance between the membrane and the electrode at the point (x,y). The Poisson equation can be solved with finite difference methods, or other numerical techniques, provided that a suitable boundary condition is used and that the right side of eq. (5) is specified.
In our case we used the IDL[8] IMSL library for the solution of the Poisson equation and for the development of the entire simulation software.

3. Numerical Simulations

The parameters that we used for these simulations are based on a ratio D/r_0 of 14. This ratio represents the mean conditions observed at Anderson Mesa, where the NPOI is located, with a r_0 of ~10 cm and a telescope of 1.4 min diameter, like the one that are being developed for the NPOI upgrade. The main statistical parameter that we will be analyzing is the instantaneous and average Strehl ratio. Each realization represents a 10 msec interval in time. The statistics of the upper layer and bottom layer are tracked using two parameters, the strength of the aberrations generated converted into a $C_N^2(h)$ profile and the time constant generating a certain Tyler and Greenwood frequency respectively. In figure 1 is shown the continuous profile of the equivalent $C_N^2(h)$ profile. This profile is consistent with a ratio of D/r_0 of 14. Different profiles and different D/r_0 ratio can easily been studied.

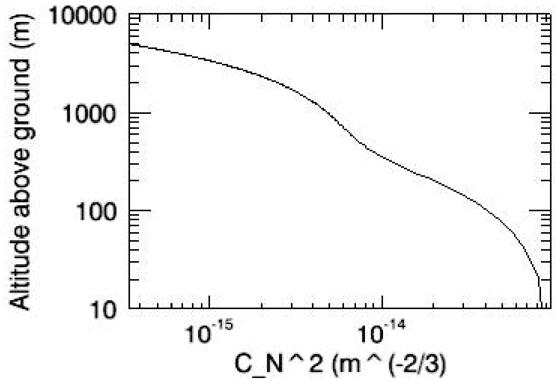

Figure 1: Continuous $C_N^2(h)$ profile

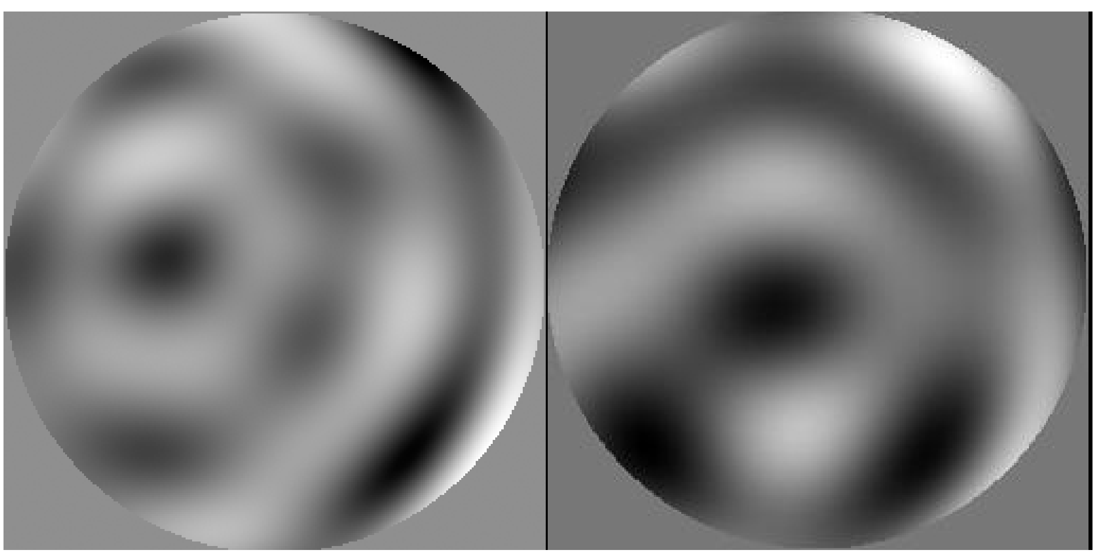

Figure 2: Example of phase screens used during the simulations. The left hand side shows the furthest phase screen while the right hand side shows the closer phase screen.

The wave is then propagated to an entrance pupil where the first DM mirror is conjugated to the higher layer of turbulence and the second DM is conjugated to the closer layer. The DMs characterized by their influence functions and the correction is applied. The second case is represented when the first DM is not conjugate to the distant layer. The study is to verify that even in this case there is a quantifiable improvement in terms of Strehl ratio when compared to the uncompensated case.

4. Analysis

The results of our simulations are presented in terms of two different parameters: the Strehl ratio and the residual wavefront error in terms of RMS error. The results are presented for both for open loop, i.e. no compensation, and for closed loop. Two cases are analyzed in terms of placing the deformable mirror(s) in the exact conjugate planes of the phase screens, or positioning the mirror(s) not at a conjugate plan and measuring the effect of such displacement on the overall correction. The residual wavefront error is verified with two independent programs: our own IDL based simulation and the OKO Mirror Fit program [9].

In figure 3 we show the results of 300 phase screen realizations, 3 seconds in time, with the Strehl ratio obtained without DMs correction, dashed line, and with DMs correction, solid line. In this case we used two DMs at the conjugate planes of the two phase screens. The only error introduced in this simulation, at this point, is the residual error due to the fitting error of the DM influence functions vs. the phase screen. No attempt at this point has been made to characterize in more realistic way the overall AO system introducing wavefront fitting errors, system lag etc.

In figure 4 are shown the results of a simulation similar to the one illustrated in figure 3, but with one DM not in the conjugate plane of the high altitude phase screen.

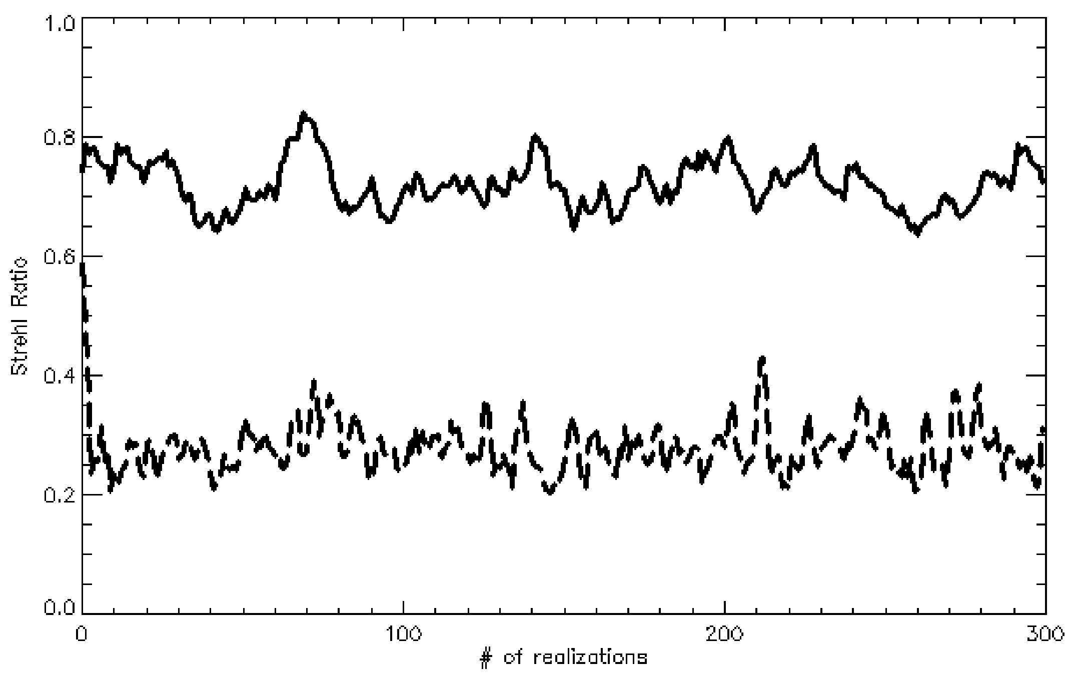

Figure 3: Example of Strehl ratio without compensation (segmented line) and with optimal compensation (solid line).

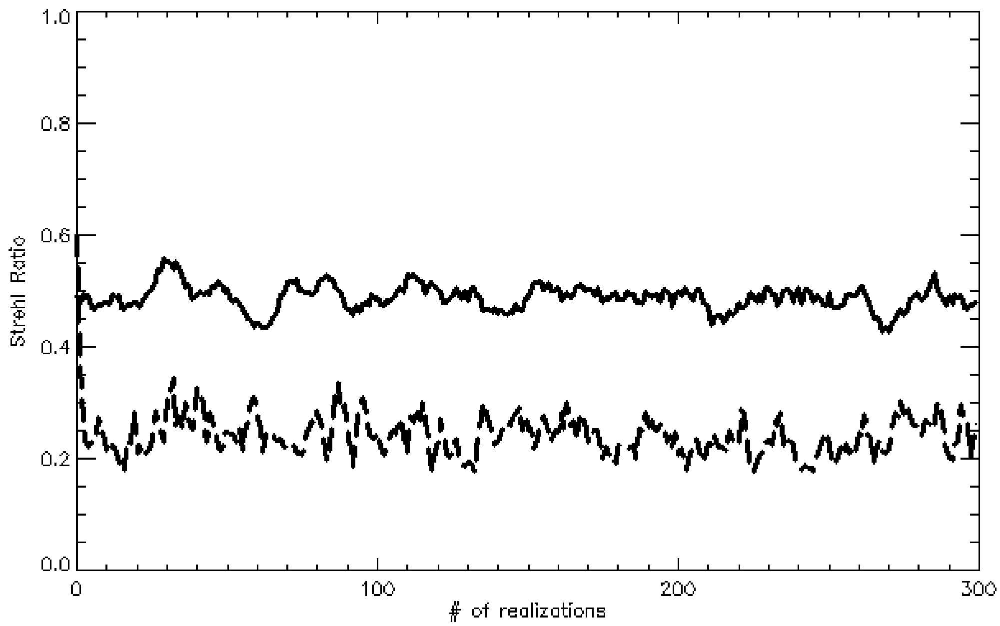

Figure 4: As in Figure 3 but this time the DM is not in the phase screen conjugate plane.

In figure 5 we show the residual wave-front error RMS in the case of close loop with both DMs in the right conjugate planes, solid line, and in the case of one DM not in the right conjugate plane, dashed line. Furthermore a similar analysis was carried out using the OKO mirror fit program. Since the mirror fit program does not handle multiple DMs we used the program in cascade to simulate the use of two DMs. We also run the mirror fit program on a sample of our realizations. The results from mirror fit are consistent and of the same magnitude that the results obtained with our simulation program.

This preliminary analysis points out that the use of two DMs, even when not in the right conjugate plane, is still beneficial. This cases are for on axis only data, i.e. we are not trying to correct a wide field of view. There evidence in many astronomical sites where the presence of a higher layer in conjunction with a lower layer of turbulence has been observed.

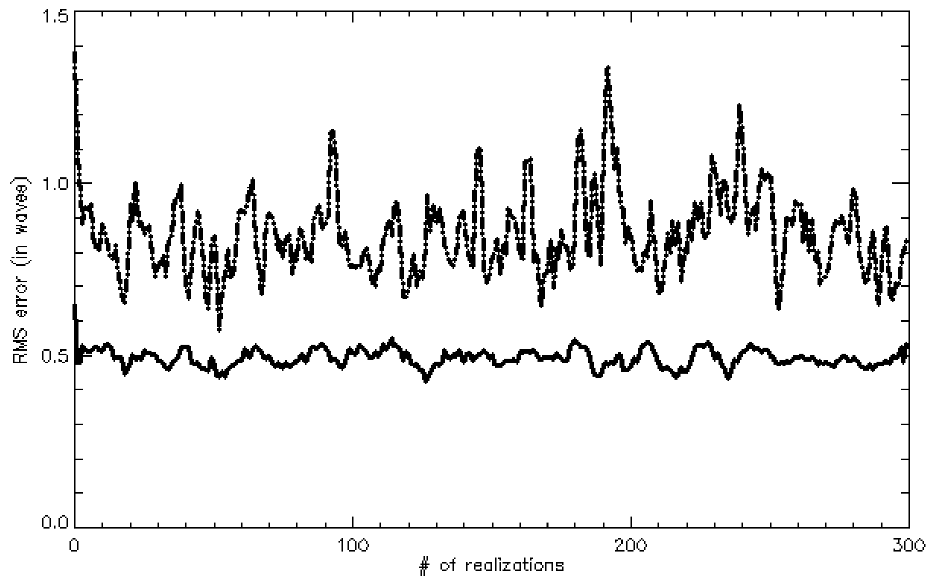

Figure 5: Residual wavefront error RMS in waves. The dashed line represents the case for one DM not in the right conjugate plane, while the solid line represents the case for both DMs in the right conjugate plane.

5. Conclusions

In this paper we have analyzed the effects of having multiple DMs at the conjugate planes of phase screens vs. not being at the conjugate plane. This second situation arises when there is an uncertainty of where exactly the higher layer of phase aberration is located or for other reasons is impossible to do a good conjugation. The analysis shows that even a non perfect conjugation will improve the overall correction. While the analysis is not completed, since several source of errors have not been included and many other cases have to be analyzed and studied, this preliminary results are encouraging and definitely indicate that having multiple DMs is advantageous.

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